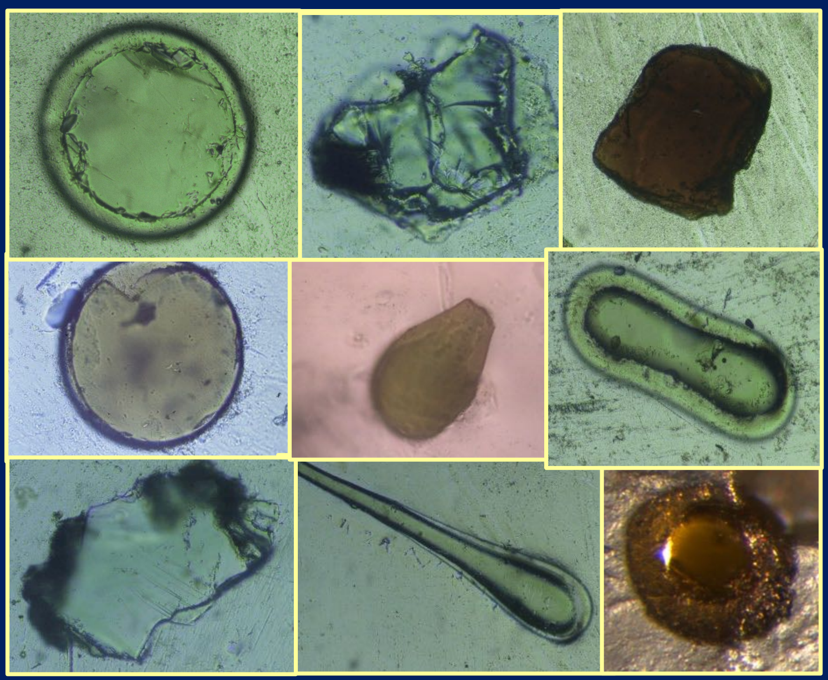
Lunar Impact Glasses: Small Samples, Big Science



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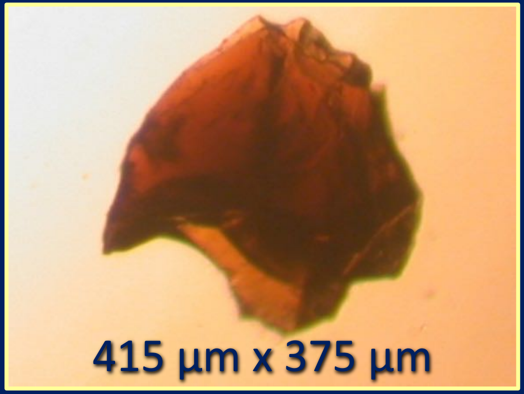
Lunar Impact Glasses

Glasses are formed when regolith is melted during a high-temperature event

→ where, when, how often impacts occurred



Glasses are small, “clean”, numerous, and optically homogeneous

Motivation: gain information about ***regolith lithologies*** AND the ***lunar impact flux***

Motivation: Lunar Lithologies

lunar impact glasses = melted regoliths

e.g., Chao et al. (1970); Glass (1971); Delano and Livi (1981); Delano (1986); Wentworth and McKay (1991); Zellner et al. (2002); Korotev et al. (2010); Huang et al. (2017)

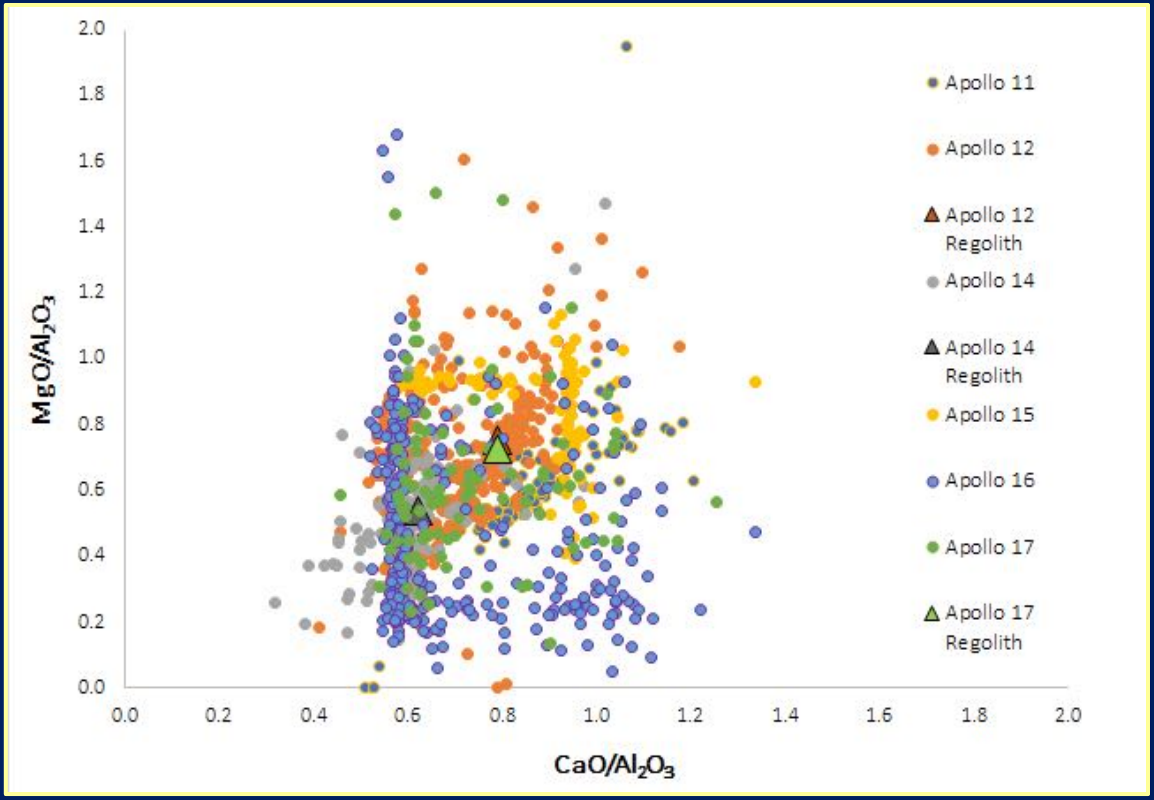
Compositions:

Regolith Transport

Subsurface material

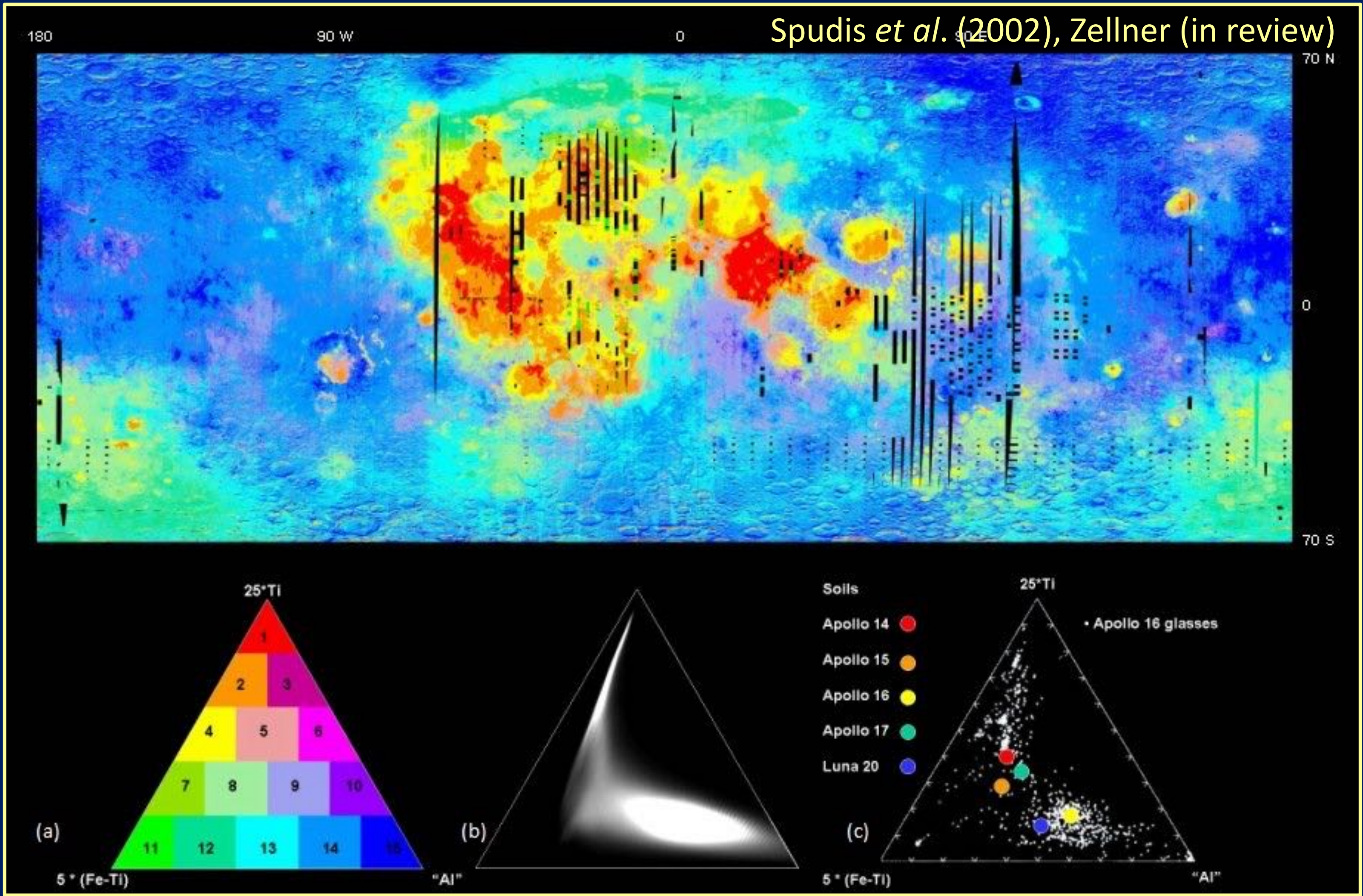
Ancient regoliths

"Grab & Go" samples



Ratios of refractory elements: regoliths & glasses (Zellner, in review)

Impact Glasses: Lunar Lithologies



Powerful tools to extract info about lunar materials

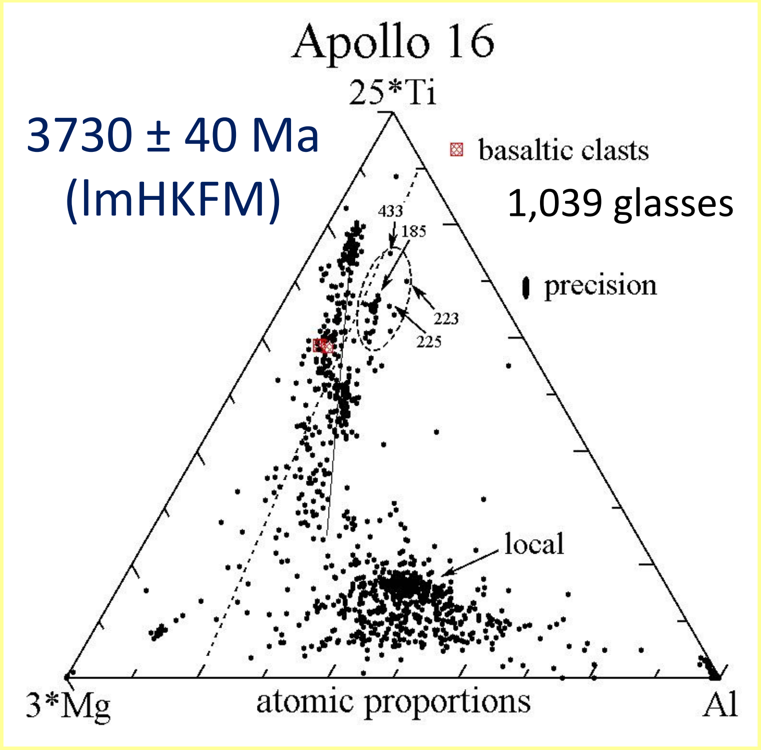
Motivation: Impact Flux

ages of lunar impact glasses = timing of impact flux

e.g., Culler et al. (2000); Levine et al. (2005); Delano et al. (2007); Zellner et al. (2009a,b); Hui (2012); Norman et al. (2012); Nemchin et al. (2013); Zellner and Delano (2015); Zellner (2017); Huang et al. (2018); Zellner (in review); Norman et al. (in review)

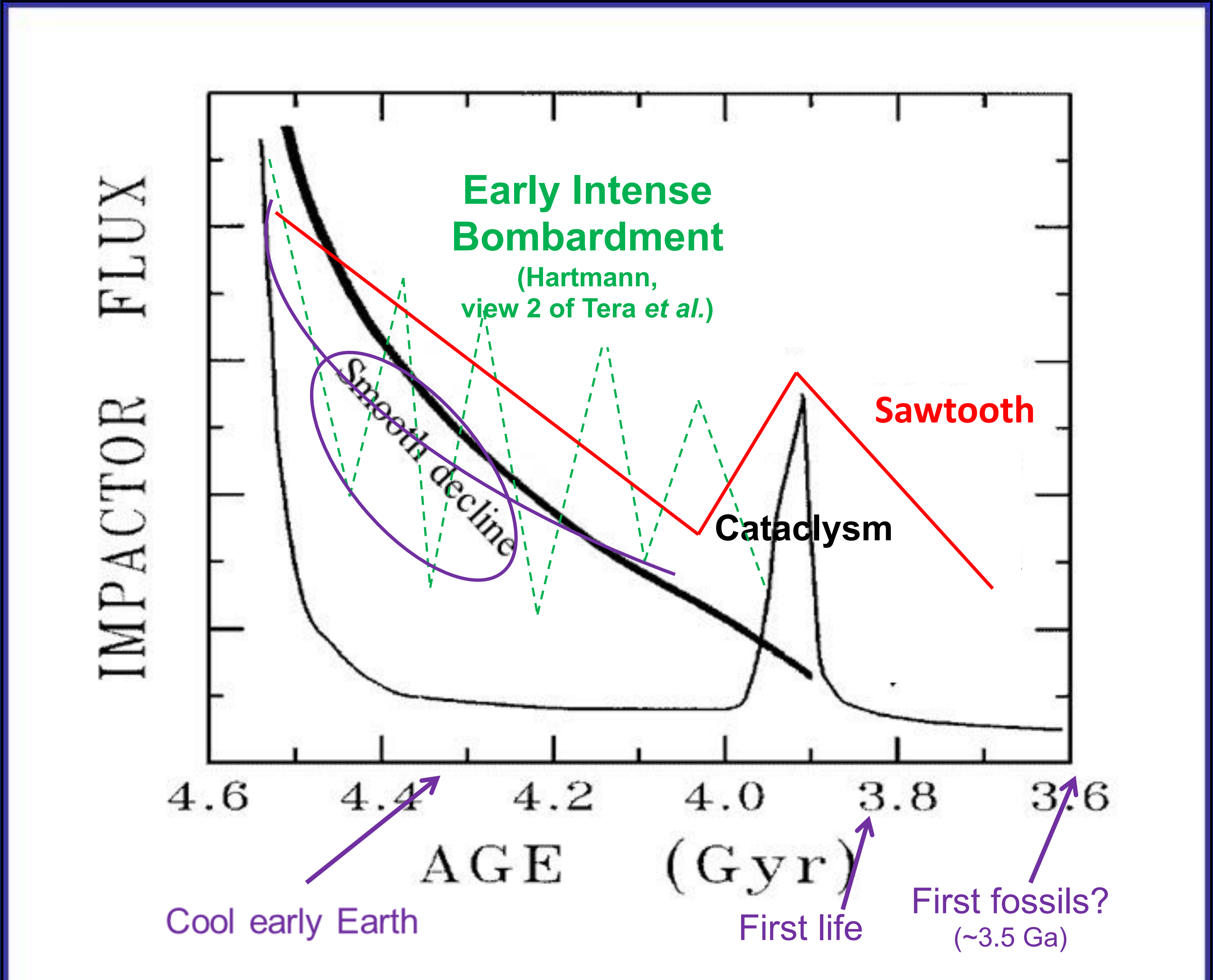
$^{40}Ar/^{39}Ar$
U-Th-Pb
U-Pb

Composition
Spheres *vs.* Shards
Size



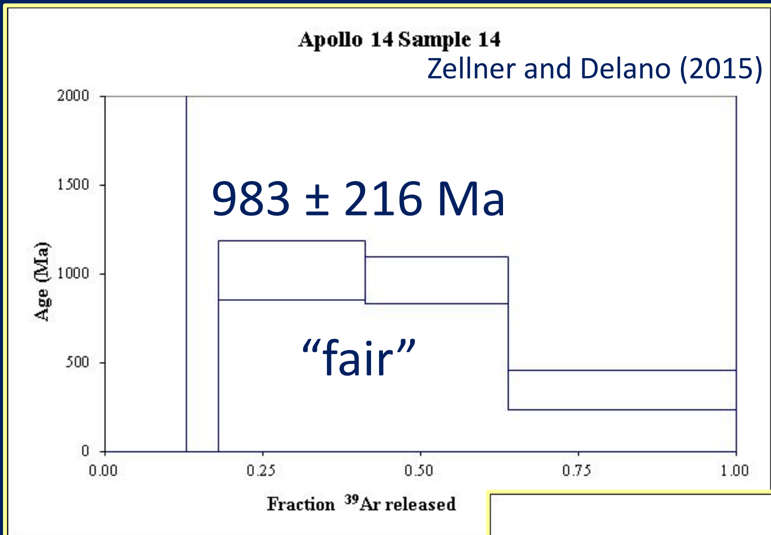
Delano *et al*. (2007): 1 large distant impact produces 4 glass shards w/ same age

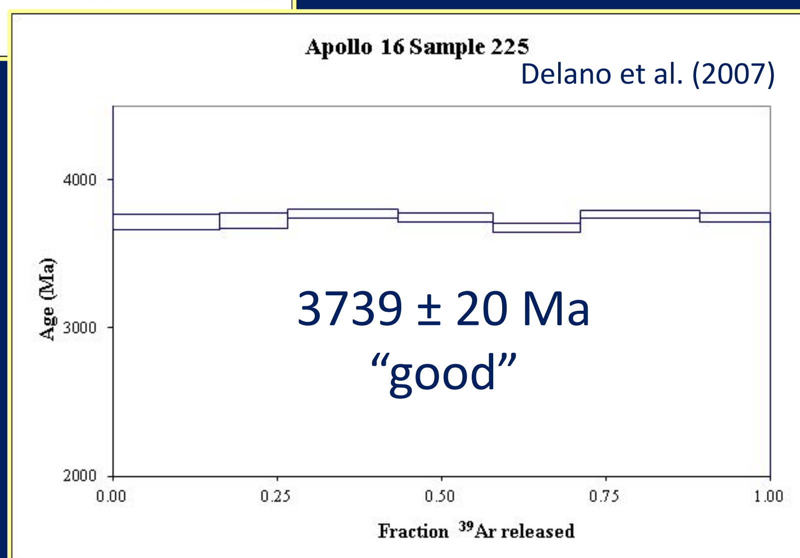
Motivation: Impact Flux



Modified from Zellner (2017); Hartmann (1965, 1966, 2000); Tera *et al.* (1974); Morbidelli *et al.* (2012, 2018)

Not All Impact Glasses Are The Same





Ar diffusivity:

Need to consider size, shape, X(NBO), K_2O (wt%) and quality of age data

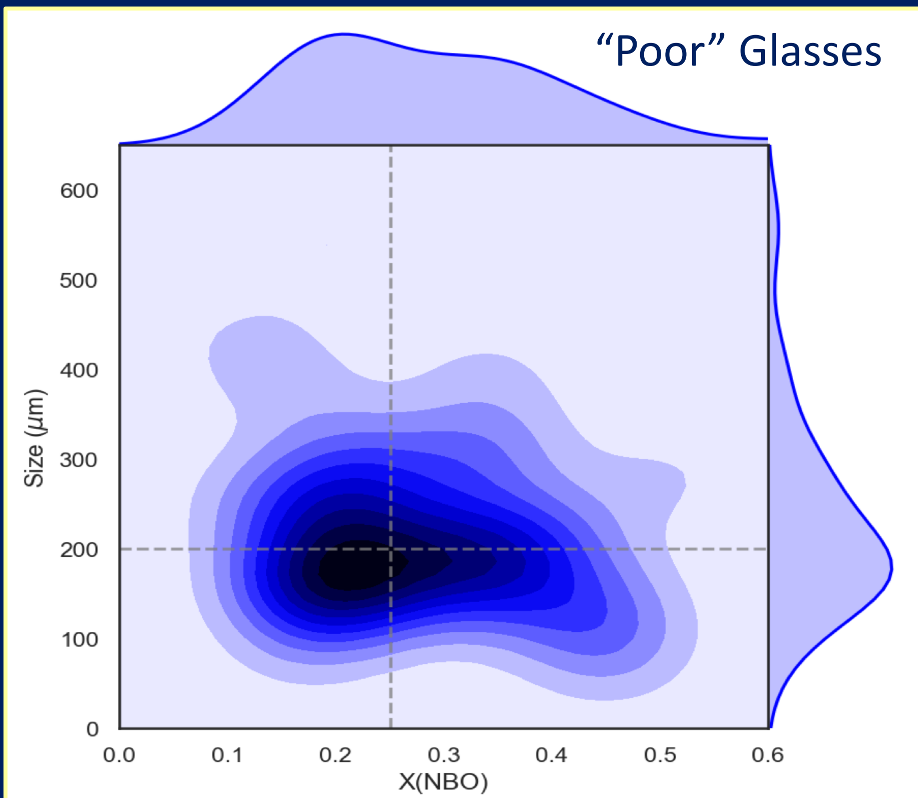
(Zellner and Delano, 2015; Nguyen and Zellner, 2019)

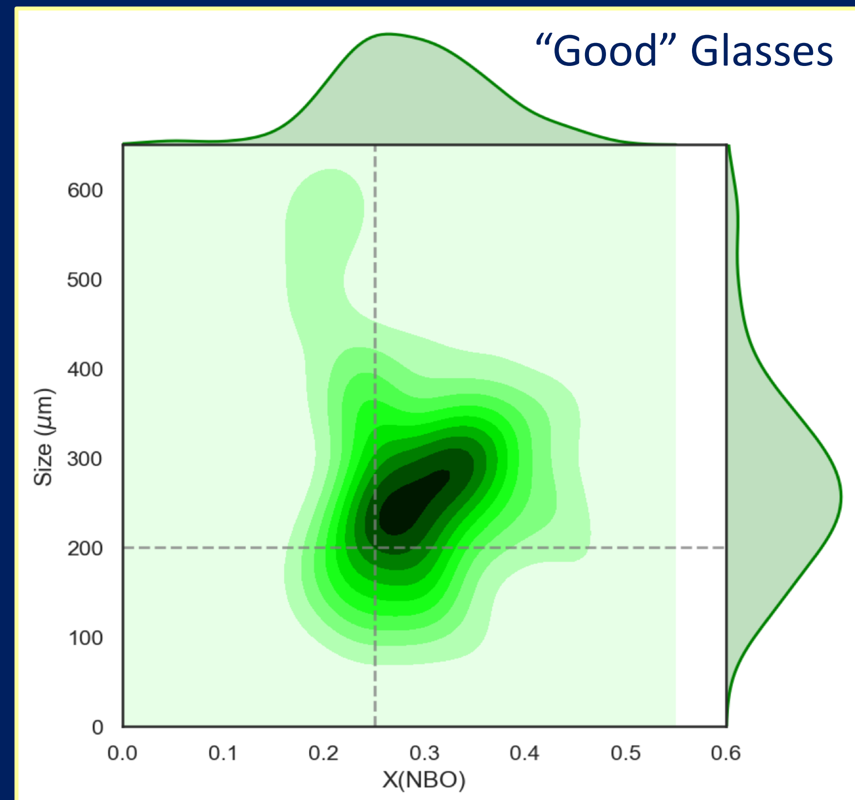
$^{40}Ar/^{39}Ar$ age "quality" affects usefulness of interpretation

Consider Composition + Size

~120 glasses: cutoff size ≥200 μm and X(NBO) value ≥0.23

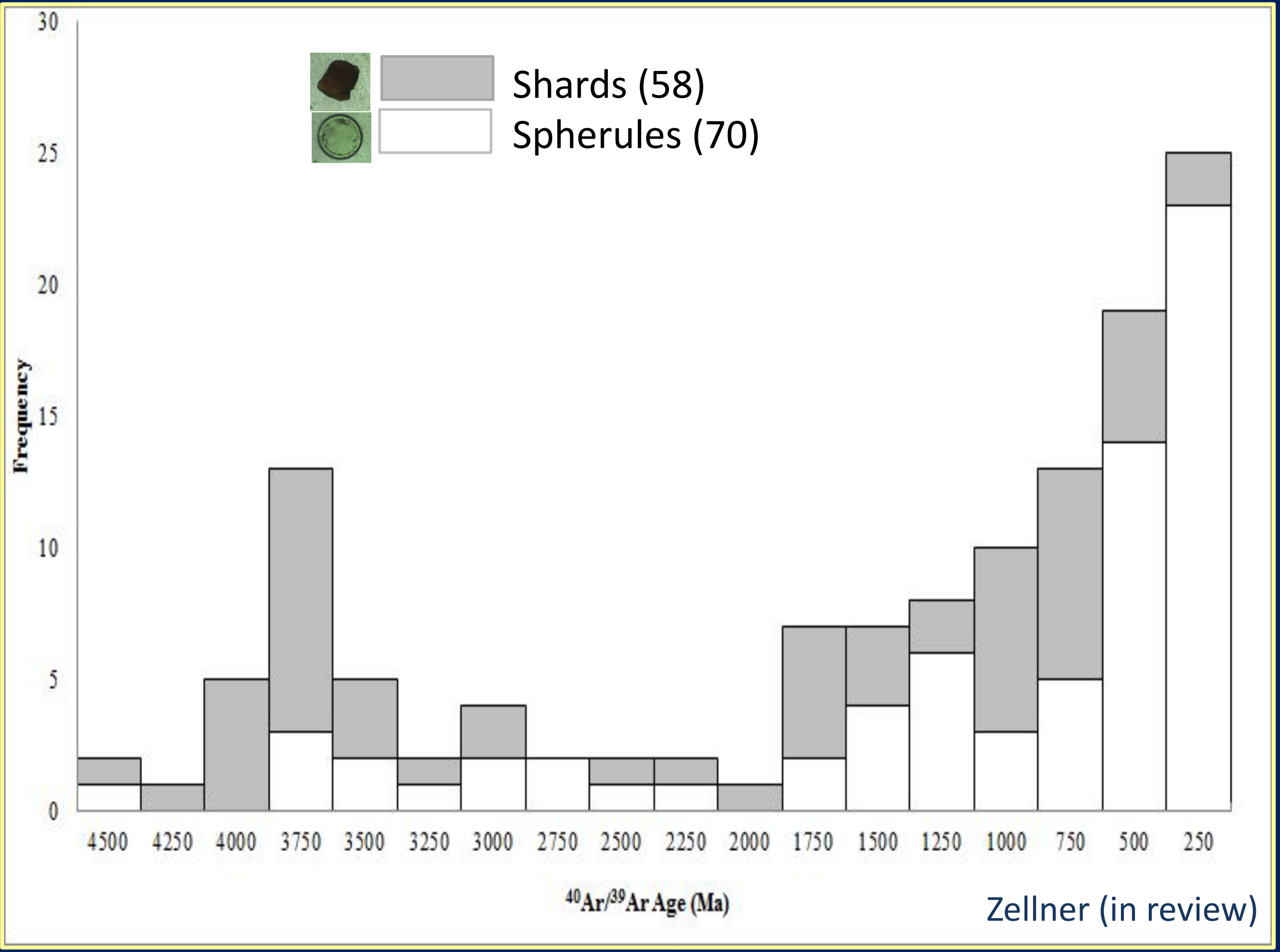
Nguyen and Zellner (2019)





Bivariate density plots of size and X(NBO): Darker shading shows higher spatial density of glasses and indicates which values are more likely to yield "good" ages

Consider Shape: Spherules *vs.* Shards



Reports of young $^{40}Ar/^{39}Ar$ ages, Pb/Pb model ages, & U–Th–Pb chemical ages on glass *spherules*

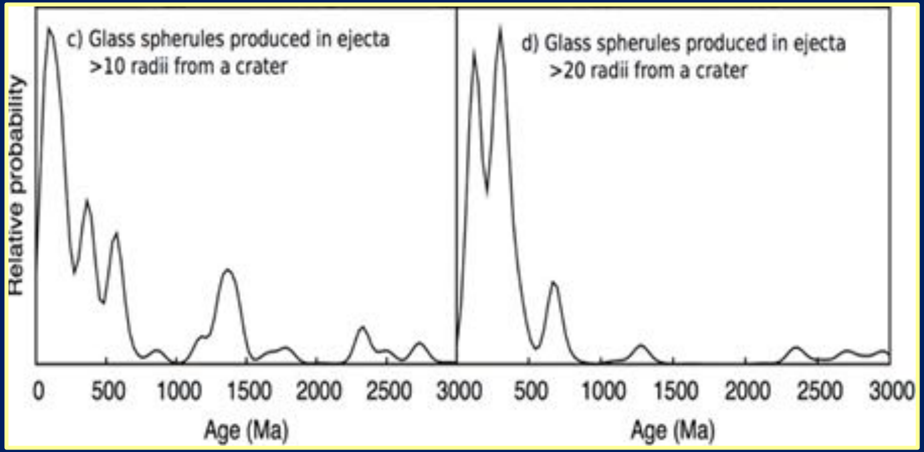
(e.g., Culler et al. 2000,
Levine et al. 2005,
Adena et al. 2009,
Hui, 2012
Norman et al. 2012,
Nemchin et al. 2013
Norman et al., in review)

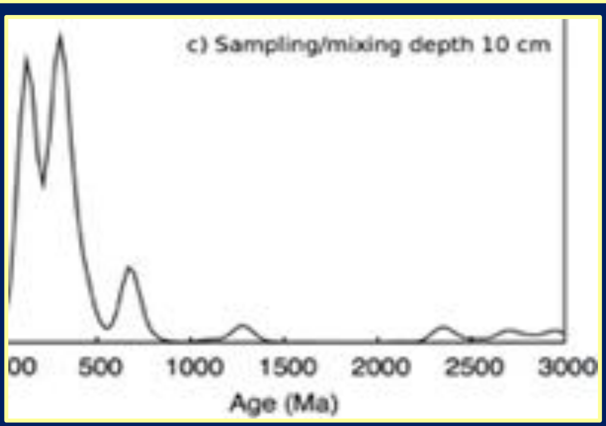
Spheres at ages ≤1000 Ma are common
Spheres at ages ≥1500 Ma are rare

Spherules: A Sampling Bias

CTEM Model: A preponderance of young sample ages is seen when

- the simulated impact depth is as shallow as 10 cm
- ejecta is beyond 10 radii from a crater



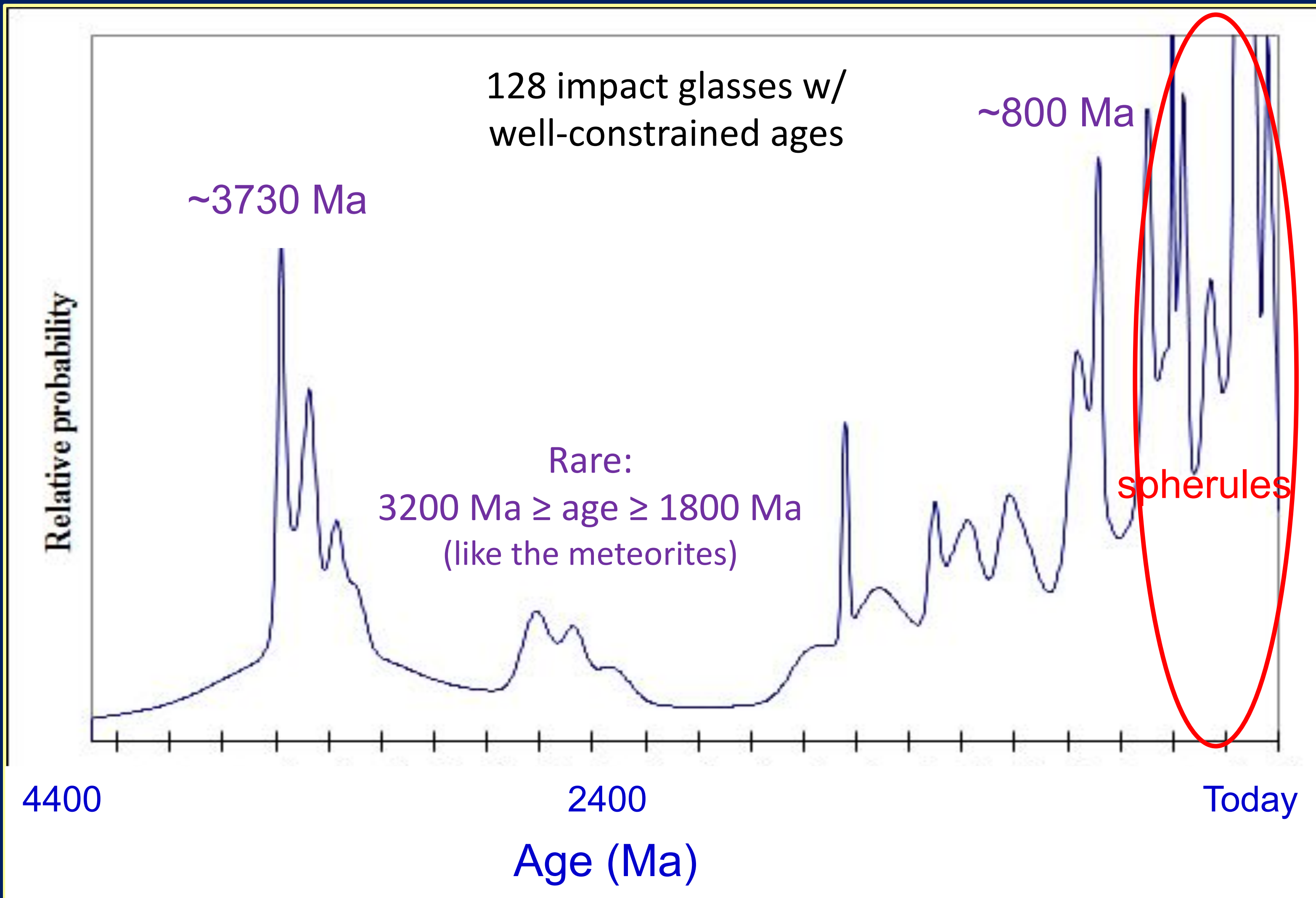


Huang *et al.*, 2018

Conclusion:

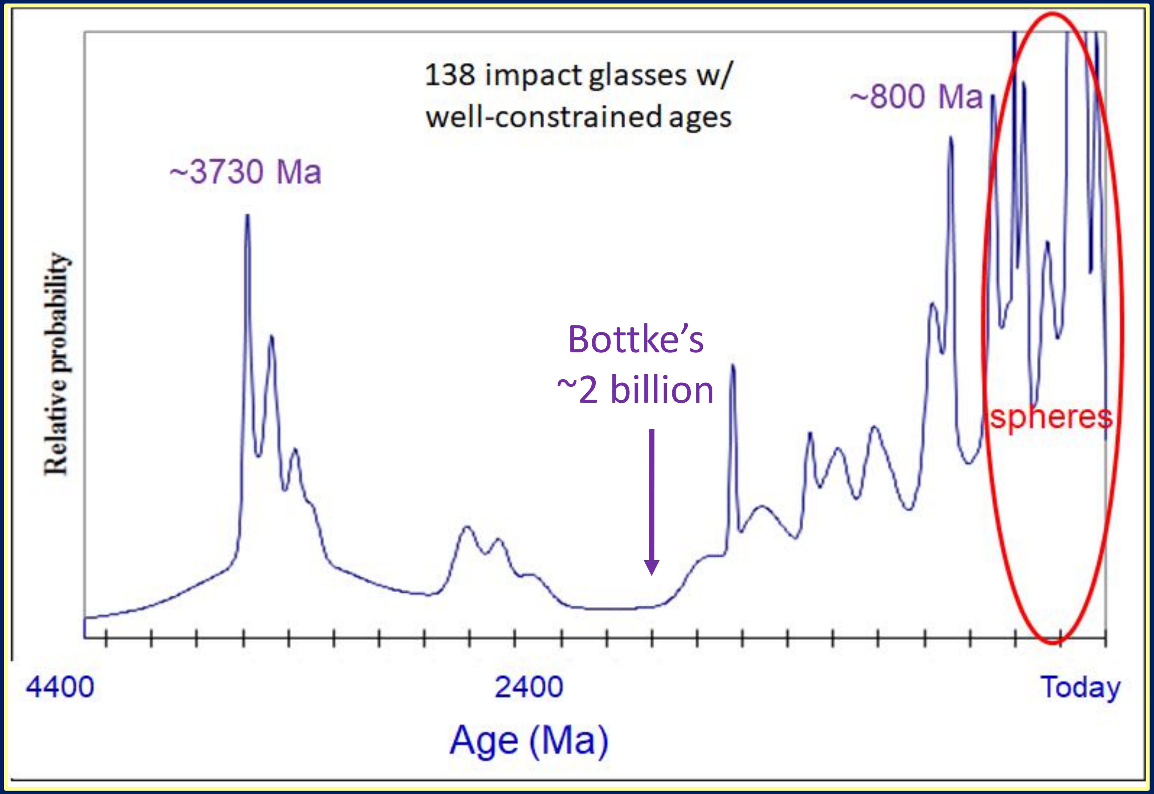
Age record of lunar impact glass *spherules* may be due to a limited sampling depth and/or Ar diffusion

Motivation: Impact Flux



Zellner (in review)

Future Work



Zellner (in review)

- Paleomagnetism

Determine what is significant

3730 Ma?

~600 Ma?

Find source craters

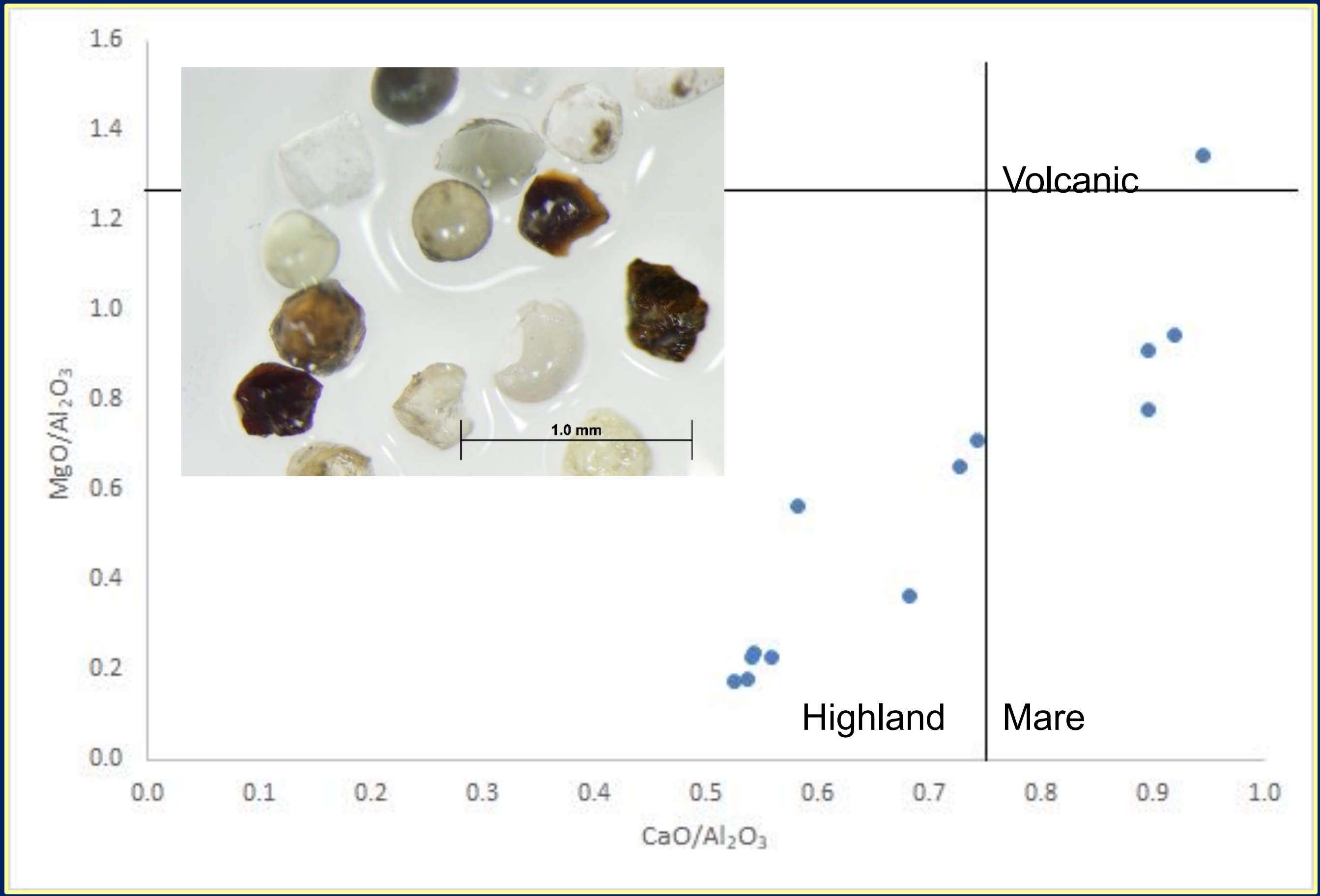
Trace elements

High-res orbital data

Solar Wind

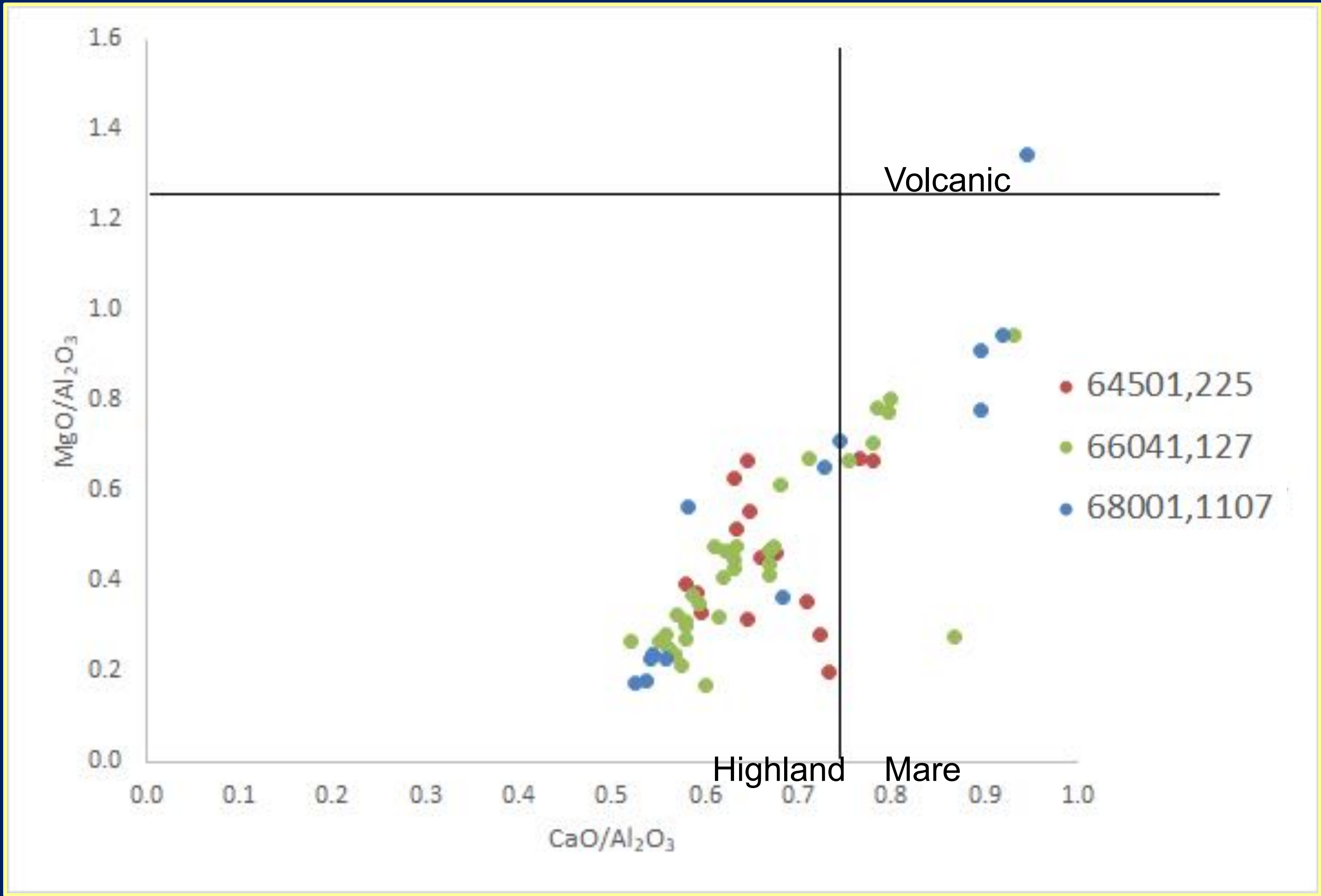
Apollo 16 Drive Tube, 68001/2

Sample 1107, ~40 cm depth



Comps: Likely to yield very good Ar isotope data

Apollo 16 Glasses



Range of ages seen in 64501, 66041 surface impact glasses

Conclusions: Transformative Science

Impact glasses are useful tools for understanding

- the Moon’s current, ancient, and subsurface lithologies and
- the Moon’s impact history, especially when interpreted in the context of lunar (and other) impact samples

Impact glasses = “Grab & Go” samples

→ abundant in any lunar regolith

→ should be abundant in regoliths of other planetary bodies

Acknowledgements

NASA LASER and SSW Programs
NSF Astronomy and Astrophysics Program

Conclusions

The accuracy and reliability of $^{40}Ar/^{39}Ar$ ages are related to size, shape, composition, and CRE age.

→ Glasses with highlands compositions are unlikely to yield old ages.

→ Spheres have lifetimes ≤1000 Ma before being broken into shards.

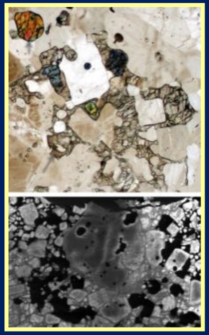
Impact glasses with ages >3500 Ma, from the tail end of the late heavy bombardment, are preserved.

Shards may be the preferred sample shape.

The Impact Flux

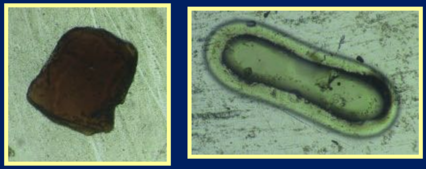
Ways to determine the time-varying impact flux:

Samples:



10s μm

- crystalline melts in Apollo samples
- crystalline melt clasts in meteorites
- zircons
- lunar impact glasses

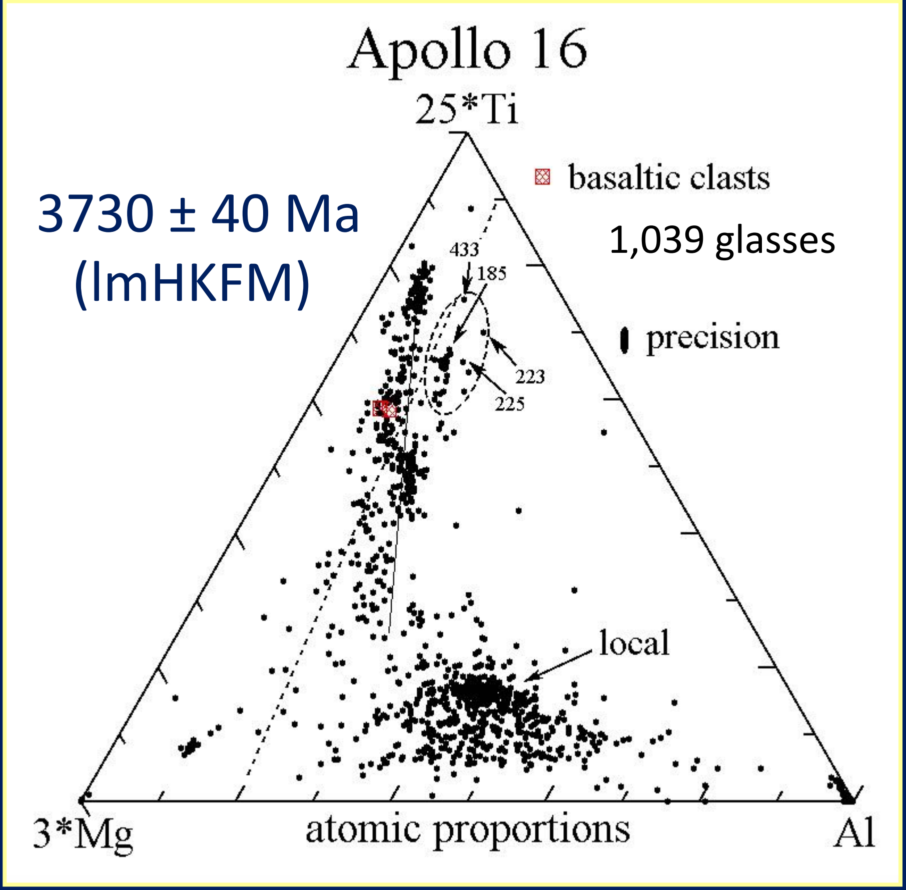


~200 μm

Other:

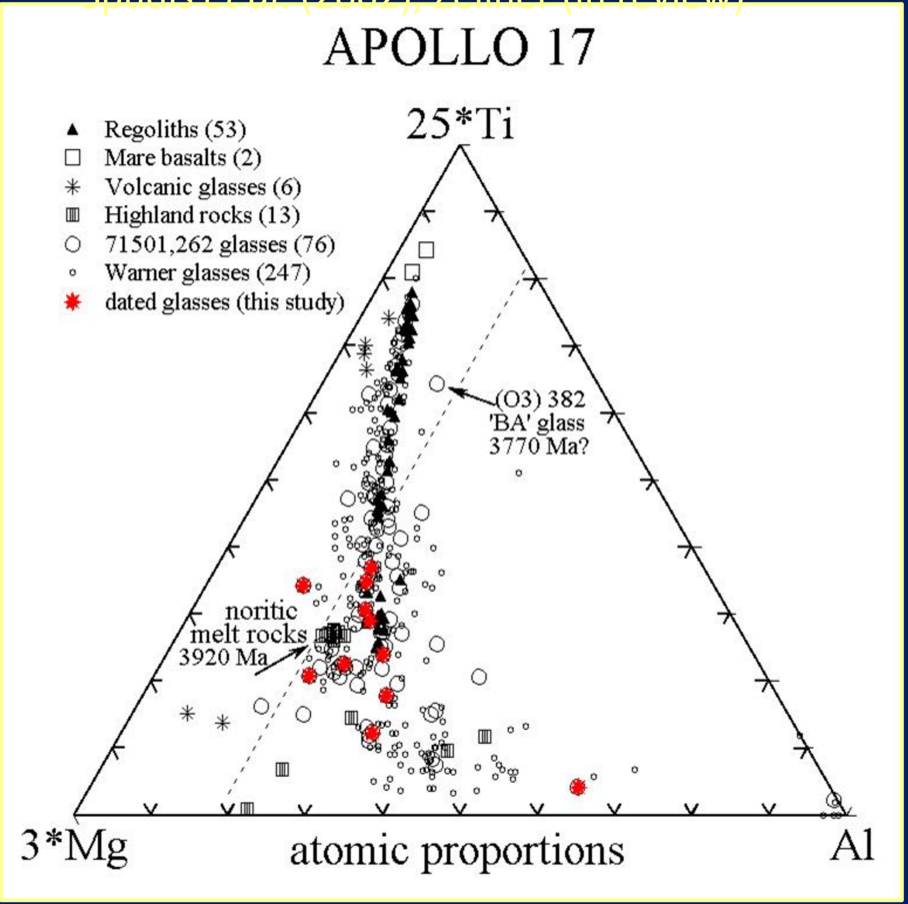
- crater counting and stratigraphy

Impact Glasses: Lunar Lithologies



Delano *et al*. (2007): 1 large distant impact produces 4 glass shards w/ same age

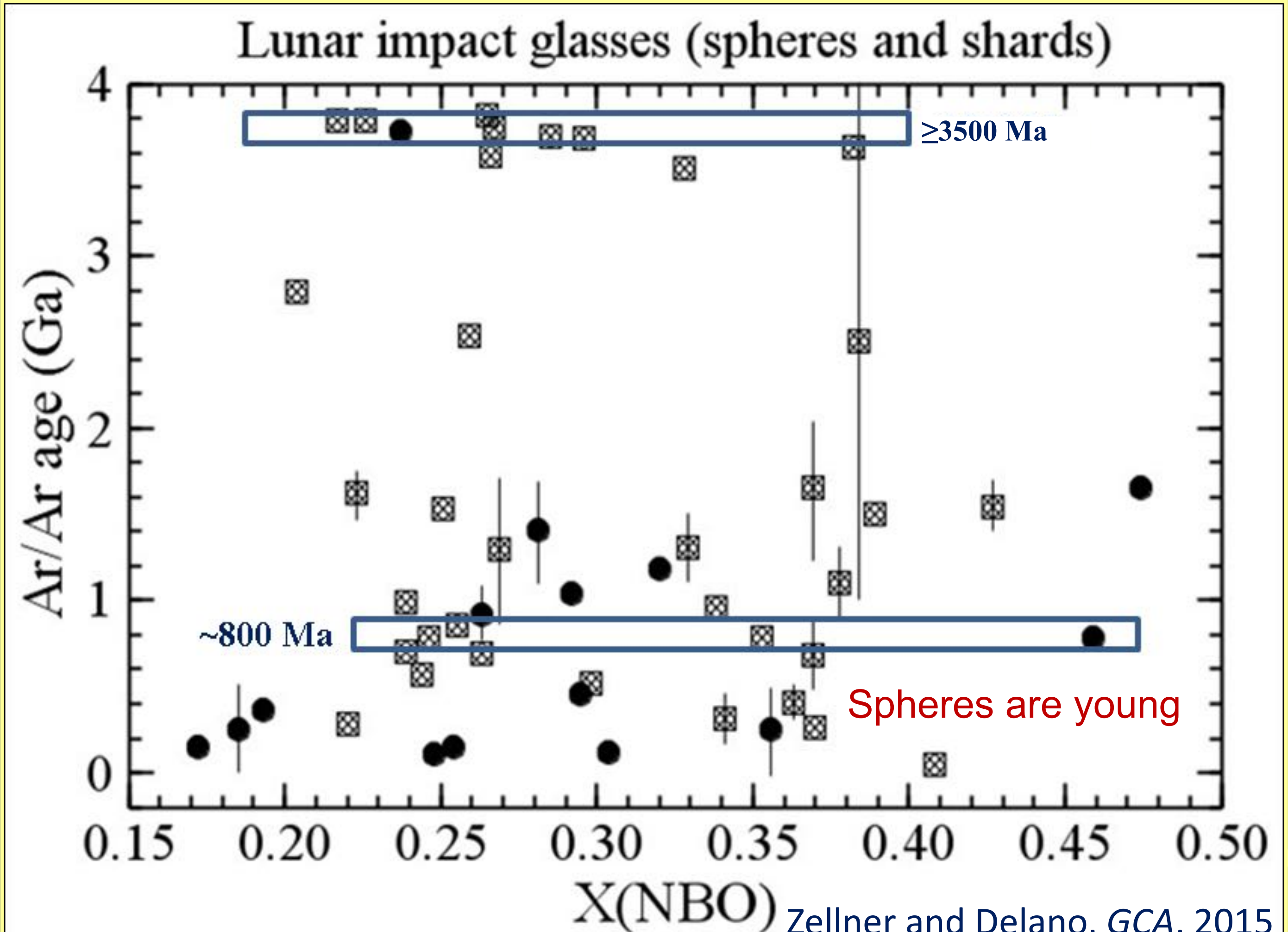
Spudis *et al*. (2002), Zellner (in review)



Zellner *et al.* (2009): Variety of impact glass compositions

Powerful tools to extract info about lunar materials

Not All Impact Glasses Are The Same



Zellner and Delano, *GCA*, 2015

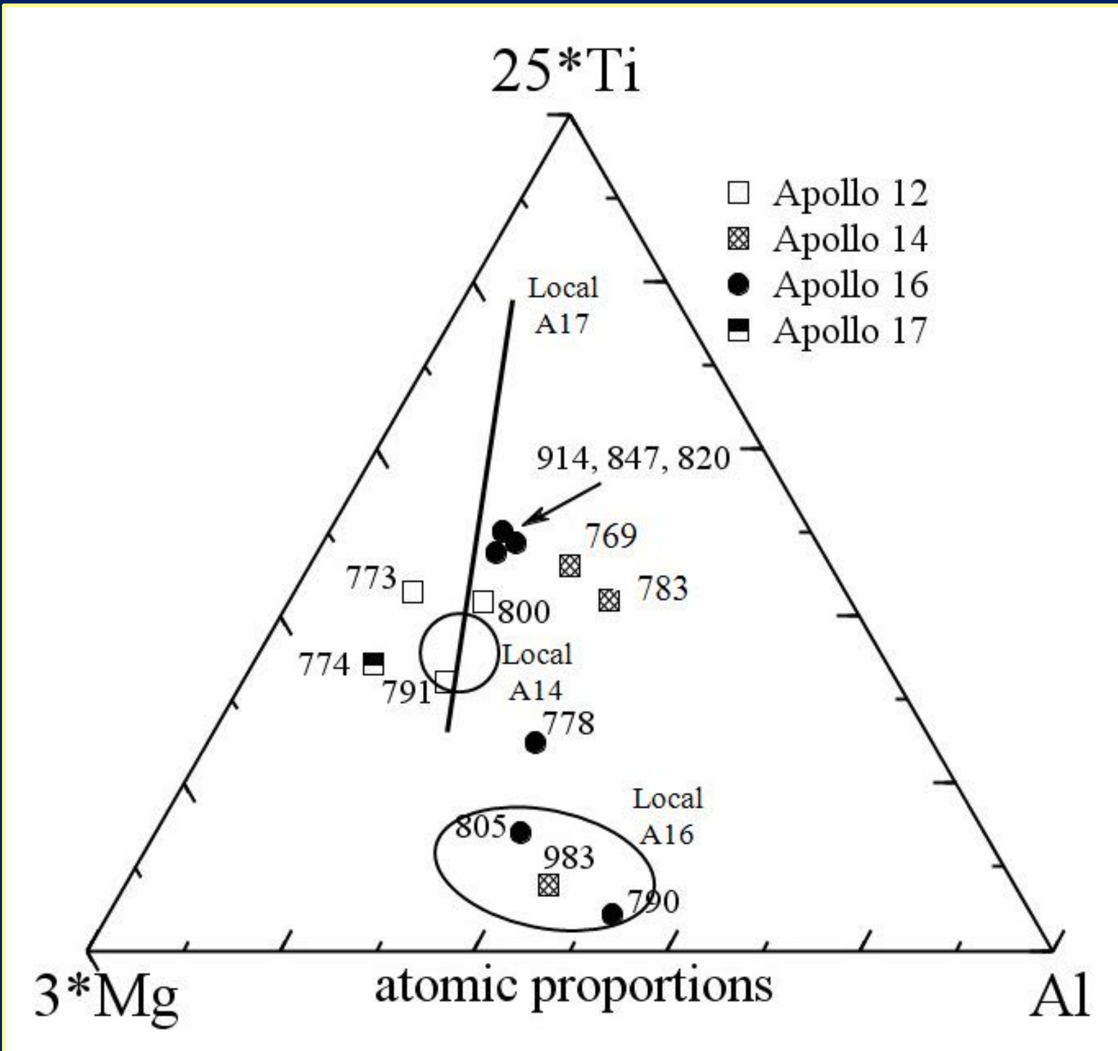
Ar diffusivity:

Need to consider size, shape, X(NBO), K_2O (wt%) and quality of age data

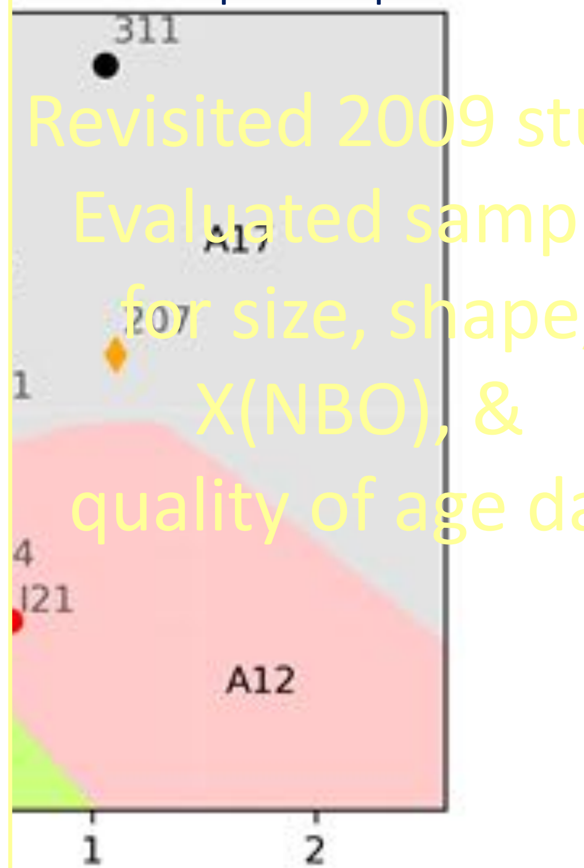
(Nguyen and Zellner, 2019)

$^{40}Ar/^{39}Ar$ age "quality" affects usefulness of interpretation

Case Study: ~800 Myo Impact Glasses



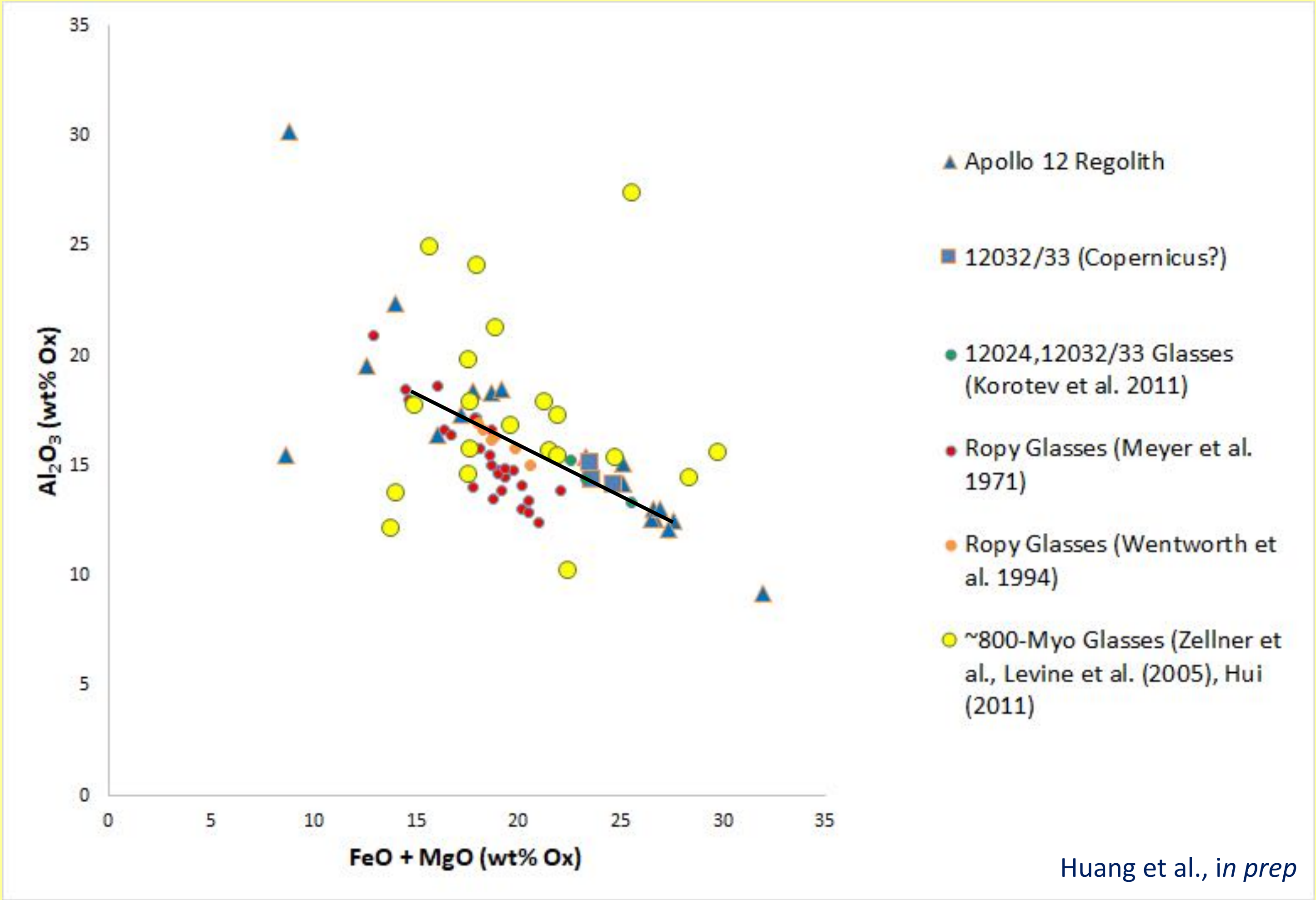
15 samples, 4 landing sites
Multiple compositions



Revisited 2009 study:
Evaluated samples
for size, shape,
X(NBO), &
quality of age data

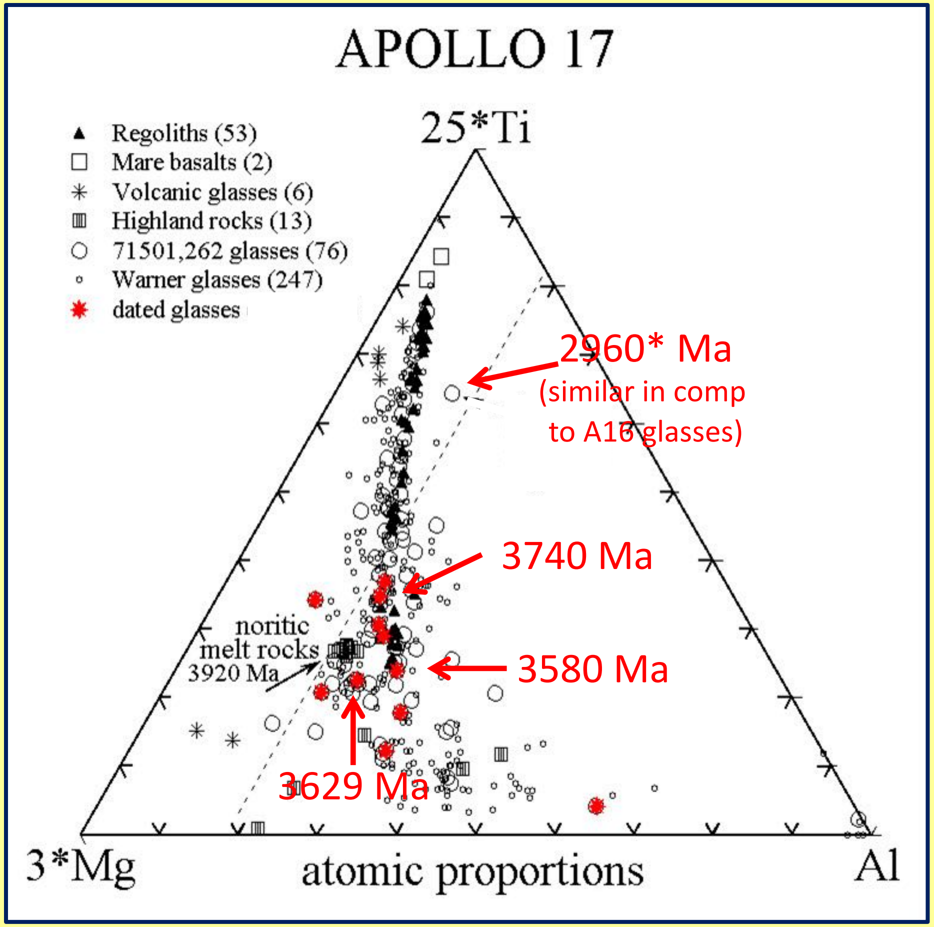
Huang et al. , *in prep*

800 Myo Glasses: Copernicus?



Probably not (& ~800 Ma ages in other samples + craters)

Case 1: Impact Glasses ≥3500 Myo

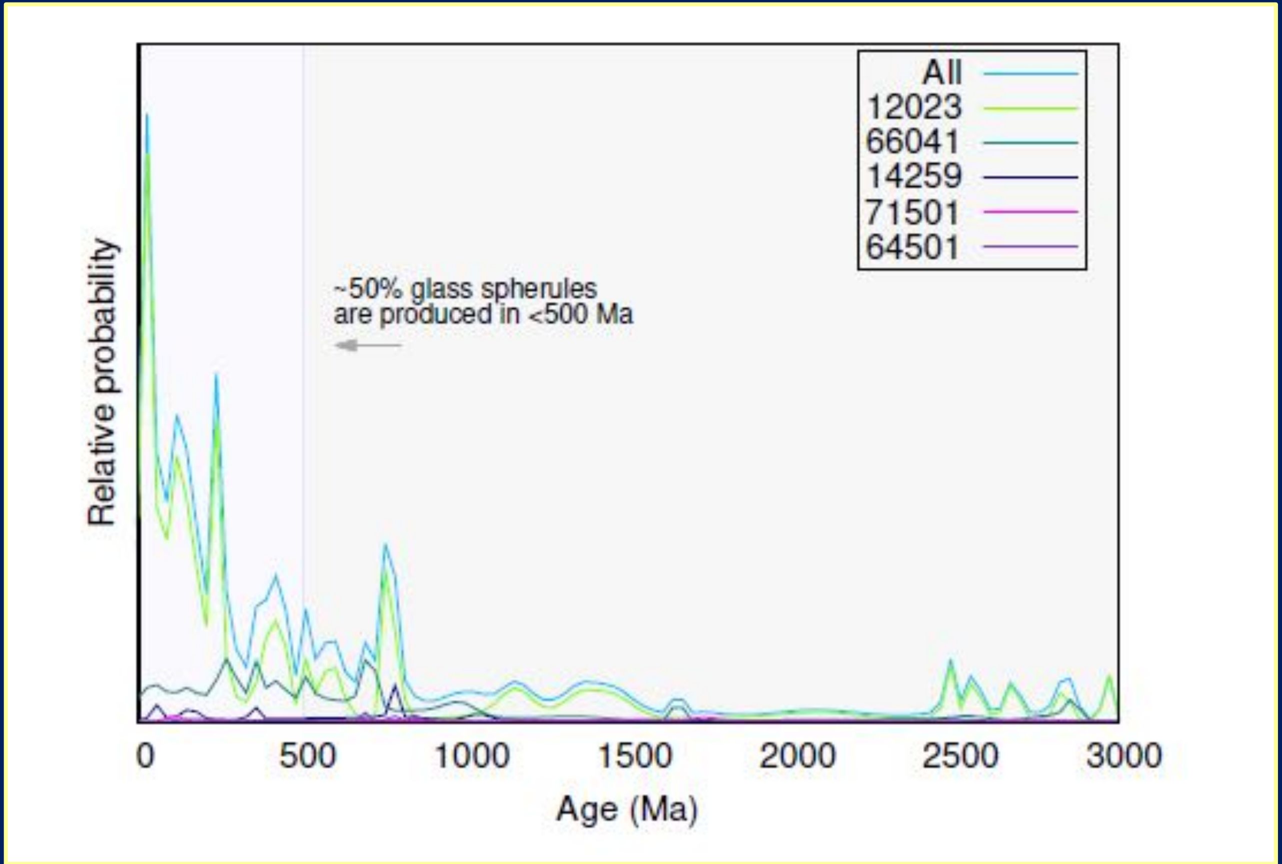


Sample Number	Age ± 2σ (Ma)	Shape	X(NBO)	Quality of Age Plot
293	3740 ± 50	shard	0.27	good
369	3630 ± 40	shard	0.38	good
390	3580 ± 45	shard	0.25	good
375	3475 ± 452	shard	0.26	fair
393	3316 ± 1198	sphere	0.29	fair
382	2960 ± 1600	shard	0.24	fair

Modified from Zellner et al., *MAPS*, 2009

* large error!

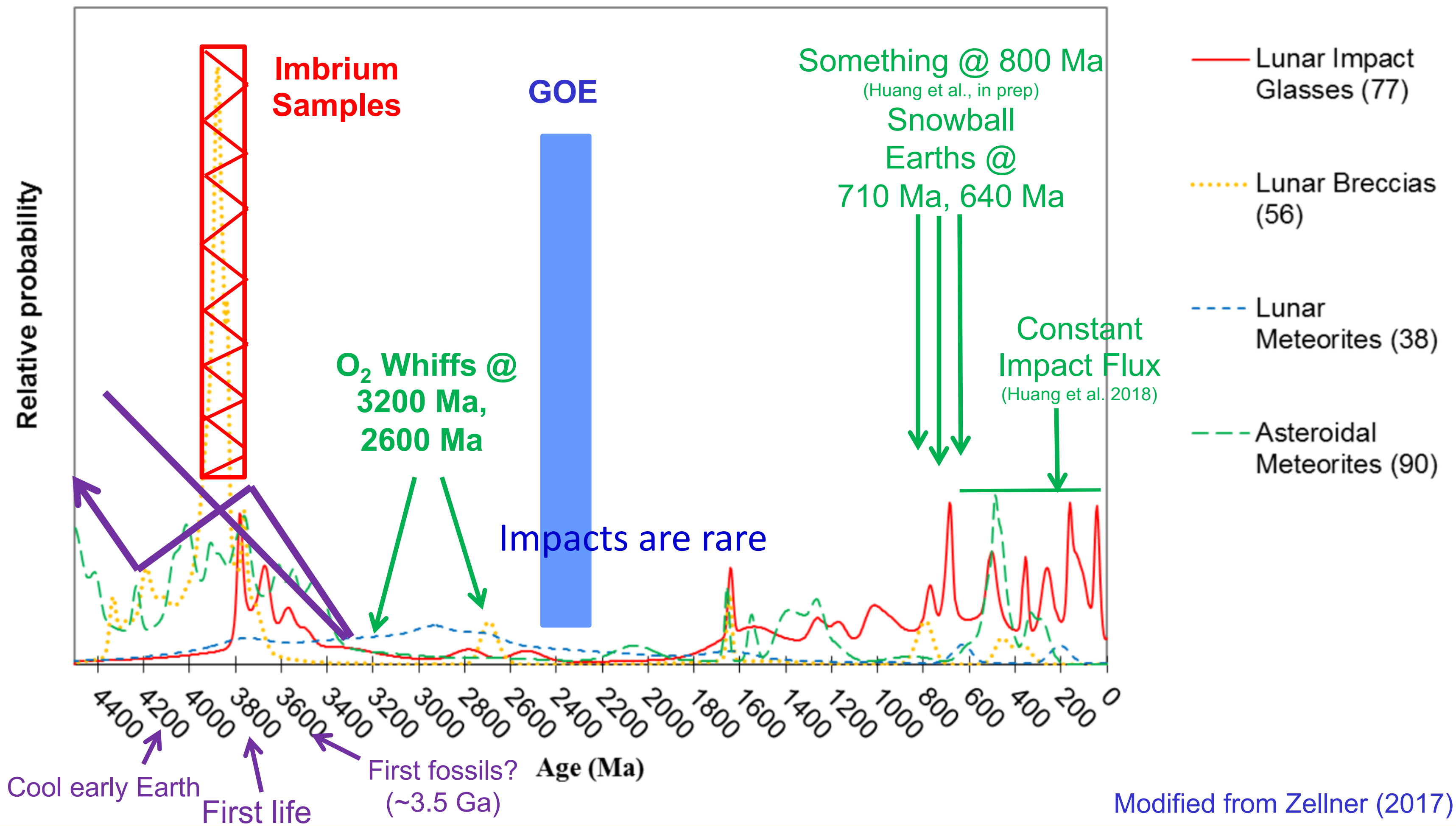
So What About the Recent Flux?



Huang *et al.*, Abstract #2677

Reports of young $^{40}Ar/^{39}Ar$ ages on glass spherules and young Pb/Pb model & U–Th–Pb chemical ages (Adena et al. 2009, Norman et al. 2012)

Timeline: Impact Flux + Life



Modified from Zellner (2017)